

# Pions in isospin asymmetric matter and nuclear Drell-Yan scattering

C. L. Korpa

*Department of Theoretical Physics, Janus Pannonius University, Ifjusag u. 6,  
7624 Pecs, Hungary*

A. E. L. Dieperink

*Kernfysisch Versneller Instituut, Zernikelaan 25, NL-9747AA Groningen, The  
Netherlands*

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## Abstract

Using a self-consistent delta-hole model the pion propagation in isospin asymmetric nuclear matter is studied. In neutron-rich matter, corresponding to heavy nuclei, a significant difference in positive and negative pion light-cone distributions is obtained leading to a nuclear enhancement of up antiquark distribution compared to the down antiquark one. This means that the sea-quark asymmetry in the free nucleon cannot be extracted model independently from an experiment on a neutron-rich nucleus.

*Key words:* Isospin-asymmetric medium; Drell-Yan scattering; Antiquark flavour asymmetry.

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## 1 Introduction

The meson-cloud model plays an important role in dealing with non-perturbative Quantum Chromodynamics effects in the nucleon. It has been used by several groups to interpret momentum distributions of sea quarks in the nucleon [1–5], measured in deep inelastic scattering. The standard approach is based upon the Sullivan process [6], in which the only essential parameter is the cut-off in the pion-nucleon-nucleon vertex.

Originally the emphasis was mainly on the description of the isoscalar  $\bar{u} + \bar{d}$  distributions. More recently, since the observed violation of the Gottfried sum

rule, showing an excess of  $\bar{d}$  over  $\bar{u}$  in proton, the interest focussed on the properties of  $\bar{u}(x) - \bar{d}(x)$  in the nucleon, whose  $x$  dependence was measured recently [7]. The asymmetry in antiquark distributions has been interpreted mostly in terms of the pion-cloud model (a review is given in ref. [8], see also [9]), and also in a soliton model in the large- $N_c$  limit [10].

Since pion properties are strongly affected by the nuclear medium, the pion cloud plays also an important role in modelling nuclear effects on deep inelastic processes. It was used in the past in connection with the EMC effect [11–13], leading to a few percent enhancement of the structure-functions ratio around  $x = 0.2$ . Similarly, most approaches predicted a nuclear enhancement of the pion field and hence the  $\bar{u}(x)$  and  $\bar{d}(x)$  distributions, leading to a noticeable increase in the predicted Drell-Yan (DY) cross-section ratio. On the other hand experimentally the DY scattering on nuclear targets [14] did not show much evidence for enhancement over nucleon targets. Several papers have dealt with this discrepancy, pointing out different mechanisms leading to reconciliation with the measurements [4,5,15,16].

For the purpose of presenting our results we find it convenient to separate them into two aspects. The calculation of experimentally measured proton-nucleus to proton-deuteron DY cross-section ratio is our first aim. The isospin asymmetric medium affects the various isospin states of the nucleon's pion cloud differently, leading to an excess of up antiquarks over down ones (even if the distributions in free proton are identical) for nuclei with more neutrons than protons. Since the charges of up and down quarks are different, the effect also shows up in the nuclear DY scattering cross section. In addition to presenting the DY ratio, one can also investigate possible nuclear effects on the difference  $\bar{u}(x) - \bar{d}(x)$  for a nucleon in the medium. It has been pointed out by Kumano that in a neutron-excess nucleus there could be medium effects contributing to this difference, coming from flavor-asymmetric parton recombination in the small Bjorken- $x$  region [17]. The mechanism he considered contributes only at relatively small  $x$  values ( $x < 0.1$ ) and the effect is also rather small (2–10% of the observed asymmetric sea in the nucleon).

In the present calculation we extend the effective field theory approach to compute pion properties in isospin-symmetric nuclear medium [18] to the case of arbitrary proton and neutron densities. Then we use the pion-cloud model [16] to compute the medium-modified quark and antiquark distributions and the proton-nucleus DY cross section. We assume that the medium effects solely originate from a modification of the pion cloud.<sup>1</sup> The nucleons are treated in

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<sup>1</sup> It is known [19] that the pion and other mesons cloud cannot account completely for the antiquark distribution of the nucleon. For example, gluon splitting gives a sizeable contribution at small  $x$  and large  $Q^2$ , but this contribution is approximately flavor symmetric [19] and thus should not modify our results significantly.

mean field approximation, while the delta-isobar and the pion are dressed self-consistently. The effects of short-range baryon repulsion are included through Migdal's  $g'$  parameters ( $g'_{NN}$ ,  $g'_{N\Delta}$ ,  $g'_{\Delta\Delta}$ ). Sensitivity of the pion distribution to the delta-hole self-energy was already recognized in ref. [11], thus we carried out the computation with the self-consistently determined in-medium delta-isobar spectral function [18].

We compute the pion light-cone momentum distributions separately for the three charge states as a function of the asymmetry parameter  $\beta \equiv (N - Z)/A$ . For  $\beta > 0$  the  $\pi^-$  distribution exceeds that of  $\pi^0$ , which in turn is larger than the  $\pi^+$  distribution, as expected on the basis of particle-hole self-energy relationships.

## 2 Drell-Yan cross section

The Drell-Yan cross section for the process  $p + A \rightarrow \mu^+ \mu^- X$  is given by (suppressing the  $Q^2$  dependence)

$$d^2\sigma = \frac{4\pi\alpha K(x_1, x_2)}{9sx_1x_2} \sum_f e_f^2 [q_f(x_1)\bar{q}_f(x_2) + \bar{q}_f(x_1)q_f(x_2)] dx_1 dx_2, \quad (1)$$

where the sum is over all flavors, and  $x_1$ ,  $x_2$  are the longitudinal momentum fractions carried by quark of the beam and target nucleons, respectively. By a suitable selection of kinematics the values of  $x_1, x_2$  can be deduced from experiment [14].

If we consider the region  $x_1 > 0.3$  when the antiquarks in the projectile play a negligible role, the ratio of the proton-nucleus to proton-deuteron DY cross-sections takes on the form

$$R_{Ad} \equiv \frac{2}{A} \frac{d\sigma(pA)}{d\sigma(pd)} = \frac{\bar{u}_{N/A}(x_2) + \bar{d}_{N/A}(x_2)}{\bar{u}_p(x_2) + \bar{d}_p(x_2)} + f(x_1) \frac{\bar{u}_{N/A}(x_2) - \bar{d}_{N/A}(x_2)}{\bar{u}_p(x_2) + \bar{d}_p(x_2)}, \quad (2)$$

where  $f(x_1) \equiv (4u_p(x_1) - d_p(x_1))/(4u_p(x_1) + d_p(x_1))$  is close to unity. Here  $\bar{u}_p$  and  $\bar{d}_p$  are antiquark distributions in the free proton, while  $\bar{u}_{N/A}$  and  $\bar{d}_{N/A}$  are the antiquark distributions per nucleon in the nucleus, differing from the free-nucleon distributions by the medium modified pion-cloud contribution. Denoting the latter by  $\delta\bar{u}_{\pi/A}$  and  $\delta\bar{d}_{\pi/A}$  the DY ratio becomes

$$R_{Ad} = 1 + \frac{1}{\bar{u}_p(x_2) + \bar{d}_p(x_2)} \left\{ \delta \bar{u}_{\pi/A}(x_2) + \delta \bar{d}_{\pi/A}(x_2) + \beta f(x_1) \left[ \bar{d}_p(x_2) - \bar{u}_p(x_2) + (\delta \bar{u}_{\pi/A}(x_2) - \delta \bar{d}_{\pi/A}(x_2)) / \beta \right] \right\}. \quad (3)$$

We see from the above expression that apart from nuclear effects, leading to nonzero  $\delta \bar{u}_{\pi/A}$  and  $\delta \bar{d}_{\pi/A}$ , for  $\beta \neq 0$  there is a nucleonic one [4], stemming from the nonzero value of the antiquark-distribution difference  $\bar{d}_p - \bar{u}_p$  in the free proton. This underlines the necessity to use parton distributions in accordance with latest  $\bar{d}_p - \bar{u}_p$  observations (for discussion on this point see section IV). For the relatively small asymmetries of interest for stable nuclei the ratio  $(\delta \bar{u}_{\pi/A} - \delta \bar{d}_{\pi/A}) / \beta$  appearing in the above expression is practically independent of  $\beta$ , leading to a linear dependence of  $R_{Ad}$  on it.

For the change of antiquark distributions due to pion-cloud modification we use the convolution formula [16]

$$\delta \bar{q}_{f,\pi/A}(x) = \sum_a \int_x^A \frac{dy}{y} \delta f_{\beta}^{\pi^a/A}(y) \bar{q}_f^{\pi^a}(x/y),$$

where  $\delta f_{\beta}^{\pi^a}(y)$ , given by

$$\delta f_{\beta}^{\pi^a}(y) = \frac{1+\beta}{2} (f^{\pi^a/n/A}(y) - f^{\pi^a/n}(y)) + \frac{1-\beta}{2} (f^{\pi^a/p/A}(y) - f^{\pi^a/p}(y)), \quad (4)$$

represents the change of the pion light-cone-momentum distribution per nucleon in the medium.  $f^{\pi^a/n/A}$  ( $f^{\pi^a/p/A}$ ) and  $f^{\pi^a/n}$  ( $f^{\pi^a/p}$ ) denote the distribution of  $\pi^a$  per neutron (proton) in medium and in free space, respectively. They are discussed in the next section.

### 3 Pions in isospin asymmetric nuclear medium

We consider a model consisting of pions, nucleons and delta-isobars in an infinite, spatially uniform system at zero temperature. The proton and neutron densities are given through their chemical potentials  $\mu_p$  and  $\mu_n$ . The equilibrium conditions for nucleons, delta-isobars and pions imply that the chemical potential for the neutral pion is zero, while those of charged pions are:  $\mu_{\pi^-} = -\mu_{\pi^+} = \mu_n - \mu_p$ . The antiparticles of nucleons and isobars are neglected, but a relativistic kinematics is used. The nucleons are further treated in the mean-field approximation, with momentum-independent mass ( $M_{*p} - M_p, M_{*n} - M_n$ ) and energy shifts ( $c_p, c_n$ ) modelling their binding, i.e.  $E_n(p) = \sqrt{M_{*n}^2 + p^2} + c_n$  for neutrons and  $E_p(p) = \sqrt{M_{*p}^2 + p^2} + c_p$  for protons. The Schwinger-Dyson equations without vertex corrections are

then solved self-consistently for the delta-isobar and pion [18]. The pion self-energy consists of the particle-hole and delta-hole contributions, with both imaginary and real parts taken into account, assuring correct analytical properties. Short-range baryon repulsion is taken into account through Migdal's  $g'_{NN}$ ,  $g'_{N\Delta}$ ,  $g'_{\Delta\Delta}$  parameters. The sum-rules for spectral functions of pions and deltas are checked and found to be satisfied to 1–2%.

The pion light-cone momentum distributions are then calculated, using the in-medium pion self-energy. Direct calculation of the diagrams corresponding to the pion emitted by the in-medium nucleon proceeds analogously to ref. [16], but separately for the three charge states of the pion and taking into account different neutron and proton densities (and thus different  $M_{*p}$ ,  $M_{*n}$  effective masses and  $c_p$ ,  $c_n$  energy shifts).

It is well known that  $f(y)$  can be expressed compactly in terms of an integral over the spin-isospin response function or imaginary part of the pion propagator. It is also possible to compute it directly from summing contributing diagrams [16], which represent emission of a dressed pion by a nucleon. The latter procedure we prefer for numerical reasons, since it needs computation of the pion self-energy in smaller energy-momentum region. The schematic expression for the pion light-cone distribution per nucleon has the form

$$f_{\beta}^{\pi/p/A}(y) = \frac{2}{\rho} \int \frac{d^3 p}{(2\pi)^3} \int \frac{d^3 p'}{(2\pi)^3 2E(p')} \delta(y - \frac{k^0 + k^3}{M}) |X_{\beta}^{\pi}(k)|^2,$$

where  $X_{\beta}^{\pi}$  represents the sum of relevant diagrams,  $\rho$  the nucleon density,  $k_0 = E(p) - E(p')$ ,  $\vec{k} = \vec{p} - \vec{p}'$  and  $\vec{p}$  ( $\vec{p}'$ ) is the momentum of incoming (outgoing) nucleon.

The full expression generalizing the case for isospin-symmetric medium from [16] reads (for the special case of  $\pi^+$  on proton):

$$f_{\beta}^{\pi^+/p/A}(y) = \frac{3y g_{\pi NN}^2 M_*}{2(2\pi p_{Fp})^3 M} \int_{-p_{Fp}}^{p_{Fp}} dp_3 \int_0^{\sqrt{p_{Fp}^2 - p_3^2}} p_{\perp} dp_{\perp} \int_{p'_{\perp \min}}^{\infty} p'_{\perp} dp'_{\perp} \times \int_0^{2\pi} d\theta k^2 F_{\pi NN}^2(k) \frac{1}{z'} |\tilde{D}_{\pi^+}(k_0, k)|^2, \quad (5)$$

where  $p_{Fp}$  is the Fermi momentum of the proton,  $M$  the nucleon's mass,  $M_* \equiv (M_{*p} + M_{*n})/2$ ,  $g_{\pi NN}$  the  $\pi^0 NN$  coupling and  $F_{\pi NN}(k)$  the form factor, while  $\theta$  is the angle between  $\vec{p}_{\perp}$  and  $\vec{p}'_{\perp}$ .  $\tilde{D}_{\pi^+}$  is the full pion propagator, corrected for the presence of four-fermion couplings through Migdal's  $g'$  parameters, given as  $\tilde{D}_{\pi N}$  in ref. [16],  $p'_{\perp \min} = (2z' M_* (M_{*n}^2 + p_{Fn}^2)^{1/2} - (z'^2 + 1) M_{*p}^2)^{1/2}$  if the argument of the square root is positive, otherwise is zero, and  $z' \equiv$

$(-My + p_3 + E(p) - c_n)/M_*$ . The expression for  $\pi^-$  is obtained by swapping the indices  $n$  and  $p$  and for neutral pions the total distribution is a sum of two terms corresponding to emission by proton or neutron.

The difference in distributions for the various charge states of pion basically comes from two factors. One is the Pauli blocking of the outgoing nucleon, which in neutron-rich medium restricts emission of  $\pi^+$  (from a proton, creating a neutron in the final state) more than the emission of  $\pi^-$  (since a proton appears in this case in the final state). The other effect is the dressing of the pion propagator, in which the particle-hole and delta-hole self-energies enter. Since the dominant contribution comes from the particle-hole contribution for  $N > Z$  (neutron density larger than the proton one) the  $\pi^-$  propagator is affected more than the one of the  $\pi^+$  (more details are given in the next section).

While the delta has been shown to play an important role in the asymmetry for free nucleons, the medium effects are negligible [16] and not included here, which is partially a consequence of the use of a soft pion-nucleon-delta form-factor, as obtained from a fit to pion-nucleon scattering [18]. Since the isobar's contribution for  $\beta \neq 0$  to  $\delta\bar{u}_\pi - \delta\bar{d}_\pi$  is of the opposite sign compared to the contribution of Eq. (5), as discussed in the next section, at small  $x$  inclusion of this term might result in a small decrease of the calculated isospin-asymmetry effect.

#### 4 Results and discussion

For numerical calculation we used the proton to neutron ratio of tungsten, for which there are measurements of the DY cross section [14]. The asymmetry parameter in this case is  $\beta = 0.196$  and for the Fermi momenta of protons and neutrons we chose  $p_{Fp} = 238$  MeV and  $p_{Fn} = 272$  MeV, corresponding to total nucleon density slightly below the saturation density. To take into account the different binding of protons and neutrons for the energy shifts we take  $c_p = 40$  MeV,  $c_n = 42$  MeV, with the common effective mass  $M_{*n} = M_{*p} = 0.85$  GeV, thus assuring the correct asymmetry energy of 28 MeV. For the pion-nucleon-nucleon vertex we use a dipole form-factor with cut-off  $\Lambda = 1$  GeV. We checked that varying the cut-off in the range  $0.9 - 1.1$  GeV does not change appreciably the medium effect on the pion.

In Fig. 1 we present the pion light-cone-momentum distributions for nucleons in medium and in free space (upper four curves), as well as the excess pion distributions (lower three curves). The  $\pi^+$  ( $\pi^-$ ) distributions are per proton (neutron), while that of  $\pi^0$  is per average nucleon in the medium. The neutral pions see little difference between an isospin-symmetric and an isospin-

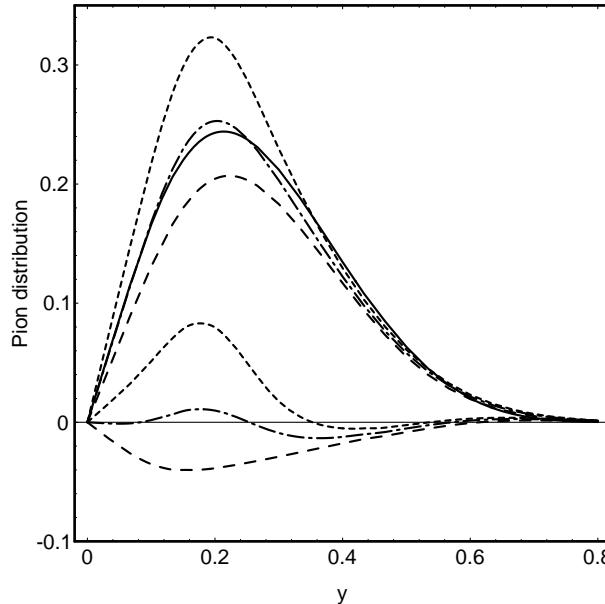


Fig. 1. Pion light-cone-momentum distributions. Full line is for free nucleon, long dashed for  $\pi^+$ , short-dashed for  $\pi^-$ , dot-dashed for  $\pi^0$ , with  $g'_{NN} = 0.6, g'_{N\Delta} = g'_{\Delta\Delta} = 0.3$ . The three lower curves show the excess distributions with respect to the free nucleon.

asymmetric nuclear medium, as long as the total nucleon density is the same (actually, the different mean-field shifts for proton and neutron may lead to a very small effect). However, for the case of neutron excess, the  $\pi^-$  distribution per neutron is larger than the  $\pi^+$  distribution per proton. This comes from a difference in particle-hole self energies, which is mainly responsible for the light-cone-momentum distributions. It is easy to understand the difference if we look at the imaginary part of the self energy as a function of pion's energy. If the energy is positive, the pion can excite a neutron from the Fermi sea to become a proton (above the proton Fermi sea) if its charge is positive. A negative pion can make from a proton in the Fermi sea a neutron above the neutron Fermi sea. Since there are more neutrons than protons in the Fermi sea, the absolute value of the imaginary part of the  $\pi^+$  self energy will be larger than that of  $\pi^-$ . Bearing in mind that in expression (5) the pion energy is negative (for the dominating part of the integratton region) and using the relation that  $\text{Im } \Pi_{\pi^+}(\omega, k) = \text{Im } \Pi_{\pi^-}(-\omega, k)$  we arrive at the inequality  $f^{\pi^-/n/A}(y) > f^{\pi^+/p/A}(y)$ , in accordance with the numerical computation. We mention that for the delta-hole self-energies the relationship between the  $\pi^-$  and  $\pi^+$  is the opposite to that of particle-hole one, i.e. for positive energy that of  $\pi^-$  is larger (in absolute value) than the self-energy of  $\pi^+$ ; a consequence of different isospin factors in the pion-nucleon-delta vertex. We see that for the studied asymmetry there is a significant difference in the distributions of three charge states. The distribution in isospin symmetric medium is very close to the  $\pi^0$  distribution.

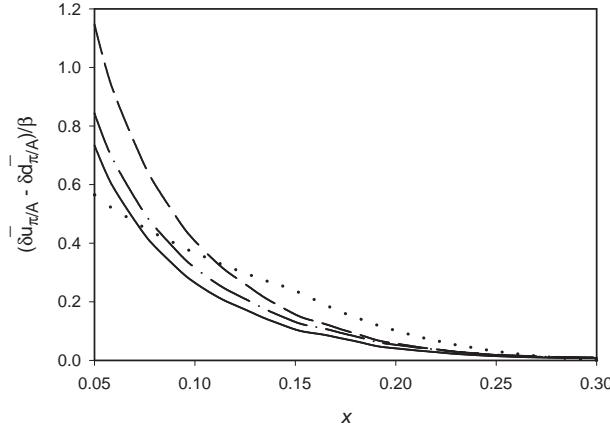


Fig. 2. The antiquark-distribution difference,  $(\delta\bar{u}_{\pi/A} - \delta\bar{d}_{\pi/A})/\beta$  per nucleon in the medium. Full line is for  $g'_{NN} = 0.6, g'_{N\Delta} = g'_{\Delta\Delta} = 0.3$ , dashed line for  $g'_{NN} = 0.5, g'_{N\Delta} = g'_{\Delta\Delta} = 0.3$  and dash-dot line for  $g'_{NN} = 0.5, g'_{N\Delta} = g'_{\Delta\Delta} = 0.4$ . The dotted line shows  $\bar{d}_p - \bar{u}_p$  for comparison.

The valence distribution of negative pions contains up antiquarks and thus in neutron-rich matter they outnumber the down antiquarks present in the positive pions, due to nuclear effects on the pion clouds. A comparison of this effect to the recently measured [7]  $\bar{d}_p(x) - \bar{u}_p(x)$  difference for proton is presented in Fig. 2. It shows the quantity  $(\delta\bar{u}_{\pi/A} - \delta\bar{d}_{\pi/A})/\beta$  compared to the mentioned  $\bar{d}_p(x) - \bar{u}_p(x)$ , to which it is added in the expression (3) for the DY ratio  $R_{Ad}$ . The quantity  $(\delta\bar{u}_{\pi/A} - \delta\bar{d}_{\pi/A})/\beta$  does not change appreciably with  $\beta$  up to its value of 0.2, but it is sensitive to the  $g'$  parameters. Existing experimental and theoretical information [15] suggests values of 0.55 – 0.7 for  $g'_{NN}$  and 0.3 – 0.4 for  $g'_{N\Delta}$  and  $g'_{\Delta\Delta}$ . These values give results consistent with observed DY scattering for the isospin-symmetric calculation [16], and we use these values also in the present case. Taking momentum dependent  $g'$  parameters (as suggested in ref. [15]) could change the details of our results. Exploration of this and other effects we leave for a future publication.

The free nucleon parton distributions are taken from ref. [20]. They fit the  $\bar{d}_p - \bar{u}_p$  and  $\bar{d}_p/\bar{u}_p$  of ref. [7] quite well up to  $x = 0.15$ . However, at larger  $x$  the measured difference  $\bar{d}_p - \bar{u}_p$  and especially the ratio  $\bar{d}_p/\bar{u}_p$  are poorly fitted [7]. To correct for this discrepancy, which would cause a significant increase in calculated  $R_{Ad}$ , we impose a constraint  $\bar{d}_p(x) = \bar{u}_p(x)$  for  $x \geq 0.3$  (by using the arithmetic mean value) and interpolate linearly between  $x = 0.15$ , when the unmodified distributions are used, and the point  $x = 0.3$ . In this way, the employed distributions fit the measurements of ref. [7] very well. From Fig. 2 we see that the two terms, whose sum appears in the square bracket of Eq. (3), are of comparable magnitude, i.e. the nuclear effect of the isovector part of the DY ratio plays as important role as the nucleon antiquark asymmetry.

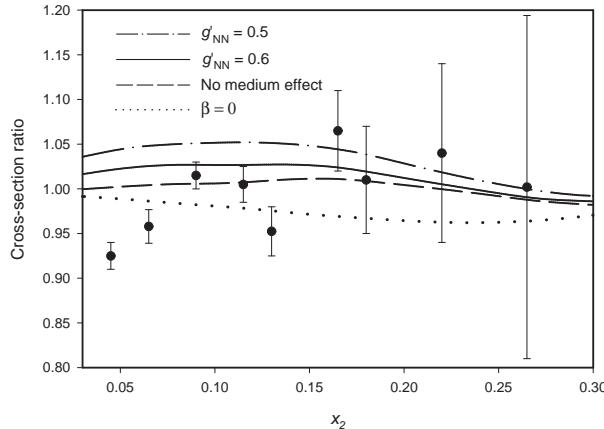


Fig. 3. DY cross-section ratio. Full (dash-dot) line is for asymmetric nuclear medium with  $\beta = 0.196$  and  $g'_{NN} = 0.6$  ( $g'_{NN} = 0.5$ ), dotted line for symmetric matter with  $g'_{NN} = 0.6$ ; in both cases  $g'_{N\Delta} = g'_{\Delta\Delta} = 0.3$ . The dashed line is for  $\beta = 0.196$ , but without nuclear pion effects. Experimental results from ref. [14] for W are shown as points with error bars.

Since the squared charge of up antiquarks is four times that of down antiquarks, the former enter in the DY cross section with correspondingly larger weight. This implies an enhancement of the DY cross-section ratio for neutron-rich medium compared to the isospin symmetric case. In Fig. 3 the ratio of cross-sections (per nucleon) is shown as a function of  $x_2$ , where both in the numerator and denominator integration over  $x_1$  is performed for  $x_1 > x_2 + 0.2$ , corresponding to the experimental situation of ref. [14]. The full line (dash-dot line) corresponds to  $\beta = 0.196$  and  $g'_{NN} = 0.6$  ( $g'_{NN} = 0.5$ ), dotted line is for  $\beta = 0$ , while the dashed line is for asymmetric medium ( $\beta = 0.196$ ), but without medium effect on the pion cloud. Measurements from ref. [14] for W are shown as points with error bars. The errors are too large for any definite statement to be made on the isospin-asymmetry effect.

We mention that the difference for larger  $x_2$  values between the  $\beta = 0$  case of Fig. 3 in the present work and Fig. 8 of ref. [16] is a consequence of the use of a more realistic dipole pion-nucleon-nucleon form-factor in the present calculation, and to a smaller extent due to a different set of parton distributions [20].

We remark that the small pion excess probability found in the present work would also lead to a pion contribution to the EMC ratio for  $x \sim 0.1$  which is smaller than in some other approaches [13]. However, this ratio is mostly sensitive to the nucleon self-energy in the medium and the role of pions is difficult to isolate.

We conclude: i) a simultaneous experiment on a neutron-rich nucleus and an  $N \approx Z$  nucleus with a 5% accuracy should in principle be able to isolate the

see up-down asymmetry (term proportional to  $\beta$  in Eq. (3)); ii) about 50% of the  $\bar{u} - \bar{d}$  difference in a nucleus comes from nuclear effects. Therefore the assumption that nuclear effects are negligible as in ref. [4] cannot be justified.

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